A Study of Wireless Sensor Networks Based Adaptive Traffic Lights Control

Sofiane BENZID[1] and Ahmed BELHANI[2]

[1] University of Constantine 1, Constantine, Algeria
sofiane.benzid@umc.edu.dz
[2] University of Constantine 1, Constantine, Algeria
ahmed.belhani@umc.edu.dz

Abstract. With the rising impact of congestion in cities, implementing an adaptive traffic light system as part of an Intelligent transportation system (ITS) is more than necessary to control traffic lights at intersections. These adaptive systems have the ability to sense traffic in real time and adjust the lights accordingly, contrary to the existing preprogrammed control systems which they fail to adapt to traffic variation causing more traffic jams. The existing industrial adaptive control systems use expensive equipment impeding their spread worldwide, but thanks to the advances in embedded systems, Wireless Sensor Networks (WSN) are emerging as a potential solution for the expensiveness of the existing adaptive schemes. In this paper, relevant works of designing an adaptive traffic lights control system using WSN are reviewed with a focus on the different sensing technologies, architectures and the algorithms used.

Keywords: Congestion, Adaptive traffic Systems, ITS, Average Waiting Time, WSN

1 Introduction

Cities and especially highly populated ones are facing a big challenge of handling congestions on their roads. Congestion arises when the transport infrastructures and the number of vehicles are not growing at the same pace leaving more and more vehicles hungry for road space [1]. According to the Urban Mobility Report published on August 2019 by the Texas A&M Transportation institute [2], In 2017, congestion made urban Americans waste 8.8 billion hours on extra travel time and consume 11.3 billion liters of extra fuel rising the cost of congestion to $179 billion. In 2013 congestion costed France €17 billion and would rise to €22 billion in 2030, €4 123 would be spent by a Parisian due to congestion compared to €2 883 in 2013 [3]. Locally in Algeria and according to a study conducted by the National Polytechnic School in 2018 covering seven highly populated cities [4], congestion costs the country €100 million per year. Traffic congestion also causes emissions contributing to air pollution and impairing human health, researches from Harvard School of Public Health (HPLS) estimates more than 2200 premature deaths and health cost of $18 billion annually in the 83 largest urban areas in USA due to congestion emissions [5].

One of the primary sources of congestion in cities are linked to the inability of existing traffic lights systems to adequately manage the flow of vehicles at intersections. Most of the existing Traffic Monitoring Controllers (TMCs) use a fixed time control to set the light plan. In the fixed time control, the sequence of the phases and the green time duration for each phase are both fixed, a phase is a combination of movements allowed to occur simultaneously without conflict and the sequence of phases where every movement is at least selected once is called a cycle [6]. The problem of this type of control is that it doesn't always favor the movement with the highest number of vehicles and it doesn't detect accidents or give priority to emergency vehicles which increases traffic congestion. As opposite to the fixed time control, the adaptive traffic control continuously detects traffic at intersections and dynamically adjusts the order of the phases and the green time duration [6]. The objective of the adaptive traffic light control is to alleviate traffic jams through reducing the average waiting time (AWT) and the average queue length (AQL) of vehicles at intersections and also give priority to emergency vehicles

The key of establishing an intelligent transportation system (ITS) is the use of sensors to collect information about traffic condition. Commonly, ITS systems rely on expensive sensors which are wired to a central entity limiting their deployment and make them more prone to faults, as a malfunctioning of the central entity leads to the malfunctioning of the entire system and cause several TLCs to be out of service or working in a predetermined manner, regardless of traffic variation. As a solution to the aforementioned problems, wireless sensor networks (WSNs) are gaining more and more attention in the literature as they are made of tiny non expensive entities called sensor nodes. These sensor nodes are easily deployed and communicate wirelessly allowing them to cover larger areas. A typical sensor node is composed of one or more sensors, a processing unit, a storage unit and a communication unit. In the adaptive traffic light systems, WSNs are used to collect information about traffic and take decisions about the traffic plan i.e. order of the phases and the green time duration. Sensors are placed in different parts of the roads or in vehicles to continuously count the number and speed of vehicles on each lane in an intersection and also to detect emergency vehicles or accidents, theses information are then passed wirelessly in a hierarchical manner up to a TMC where the traffic light algorithm is executed and hence updating the traffic plan, Figure 1 shows a typical adaptive traffic light control system using road side sensors to collect traffic information.

In the present state of the art, we review some of the relevant works regarding the implementation of adaptive traffic light controllers using WSNs focusing on the architecture and the algorithms used to reduce the AWT of vehicles at intersections and help avoiding congestions. In the second section we present some of the sensing technologies being used to detect traffic, section 3 reviews relevant works and the different strategies used to manage intersections adaptively using WSNs, section 4 summarizes the different approaches by highlighting the pros and cons of each technique and discusses some aspects towards designing a complete adaptive traffic controller. Section 5 concludes the paper.

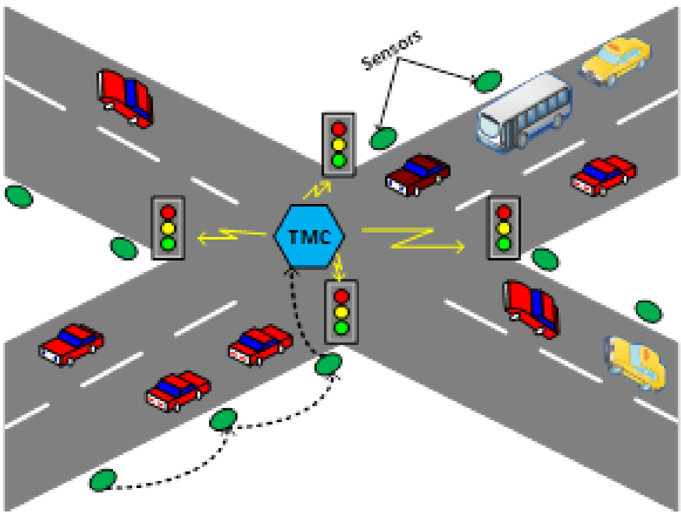

Fig. 1. WSN-Based adaptive traffic light control system

2 Sensing Technologies

Sensors are being used in ITS to detect traffic and also sometimes weather conditions affecting traffic flow. They are being used to count the number of vehicles on lanes, to measure the speed of passing vehicles and detect special events like accidents or the presence of an emergency vehicle.

2.1 Traffic sensors classification

Traffic sensors fall into two main categories depending on their placement configuration:

Intrusive sensors. This type of sensors often require pavement cut or sensors being embedded in potholes on roads. The advantage of these sensors is their higher capacity of detecting vehicles however they cause traffic disturbance during both phases of installation and maintenance raising their cost of use [7]. Inductive loops, pneumatic road tubes and magnetic sensors (when being installed under the pavement) are the most famous intrusive sensors.

Non-intrusive sensors. Or sometimes called above the ground sensors have emerged as a solution to the drawbacks of intrusive sensors thanks to their ease of installation and maintenance, making them non-disruptive to traffic flow as they are often installed on lanes, road sides or on poles like cameras and magnetic sensors, other popular above the ground sensors are [7]: RFID (Radio Frequency Identification) sensors, Acoustic sensors, Ultrasonic sensors and Infrared sensors.

2.2 Anisotropic Magnetoresistance Sensors

Among all the above-mentioned traffic sensors, Anisotropic Magnetoresistance sensors (AMR) are the most used sensors in the literature for traffic detection. Given that the earth's magnetic field is uniform, theses sensors sense the field disturbance caused by a passing ferrous object like vehicles. AMR sensors outperforms the other sensors for numerous reasons [8]: they are solid and immune to vibration, they are highly sensitive and stable when it comes to recording the magnetic signature in different climatic conditions and last but not least, they are cheap and small sized allowing their deployment on a larger scale.

Liu et al [9] employed a single 3 axis AMR sensor on a lane line to detect and measure the vehicles flow on three positions: left of the line, on the line and right of the line. The AMR used is the BMM 150. The authors developed two double window algorithms: 1) Vehicle mixed algorithms (VMR) to detect two vehicles passing at the same time, one on the left lane and the other on the right lane, with an accuracy of 98%. 2) Vehicle Motion-State Discrimination Algorithm (VMSDA) which can identify the position of the passing vehicle: left lane, right lane or on the line with an accuracy of 96,4%. The study focused on low speed vehicles without classification limiting its use only for vehicles count.

In [8] the authors designed a system for vehicle detection and classification to be used in ITS systems unlike the work in [9] where only vehicle detection was considered. The authors focused on the types of vehicles specific to the Australian roads namely: sedan, van, truck and bus. For detection purposes, the system relies on a single AMR sensor installed on the road-side 60 cm away from passing vehicles, this configuration doesn't disrupt traffic during installation or maintenance. To identify the type of the vehicle, the signal feature extraction and vector quantization techniques were applied and for system training, Dynamic Time Wrapping (DTW) algorithm is used to select the most suitable representation among the samples recorded from each passing vehicle. The effect of the distance between the AMR sensor and the passing vehicle was not investigated and hence the choice of 60 cm distance is not justified. Furthermore, the system can only detect one vehicle on a single lane hindering its use for multiple lane roads.

Santoso et al [10] used two 3-axis AMR sensors of type HMC 5883L installed on a roadside and spaced by a distance of 1m to measure the flow and speed of passing vehicles. The authors used a moving average filter to enhance the raw signal obtained by the AMR sensors and for speed measurement they took the derivative of the magnitude of both sensors to detect the steepest ascent in each signal and hence compute the time a vehicle takes to travel the 1m distance, having the time and the distance, computing the speed becomes straightforward. The results were validated using 250 fps camera. The authors didn't make mention of the distance between the sensors and vehicles and also the possibility of using the system in multiple lane roads was not evoked.

Apart from AMR sensors, other sensors are used for traffic detection: In [11] the authors used dual loop inductive detector for vehicle classification, RFID technology was used in [12] to detect emergency vehicles and give them priority at intersections and the authors in [13] surveyed many works and challenges related to traffic monitoring at intersections using cameras.

3 Relevant Works

Among the existing commercial adaptive traffic light control systems, SCOOT (Split Cycle Offset Optimization Technique) and SCATS (Sydney Coordinated Adaptive Traffic Systems) are the two most widely used ones. SCOOT works on minimizing delays and stops by predicting traffic and adjusting traffic plan through optimizing Splits, Cycles and Offsets [14]. Traffic sensors in SCOOT are placed 90 to 120 meters before intersection so it can update traffic lights before a queue is formed [15]. The implementation of SCOOT system by Siemens [14] in a corridor made of 33 intersections in the city of Seattle led to reducing travel times by 21% during rush hours, magnetometers and video detection cameras were used for traffic detection in the project. SCATS is distributed among three levels of control: local, regional and central for the purpose of coordinating multiple intersections and cover large areas [16], it relies on inductive loops for vehicle detection and push buttons mounted on traffic light poles for pedestrian detection [17]. SCATS is employed in more than 55 000 intersections in 28 countries worldwide and in which it reduced journey times by 28%, fuel consumption by 12% and emissions by 15% [17].

The abovementioned techniques and other similar techniques are expensive to implement impeding their spread in the world and especially in the developing countries, for instance on average SCOOT costs $49 000 per intersection and SCATS $60 000 per intersection without taking into account detection costs of $20 000 per intersection [18]. Designing adaptive traffic systems using WSN can be a suitable substitute for the expensive existing techniques as they rely on non-expensive and off the shelf components.

To achieve the goal of designing an adaptive traffic control system using WSN, different techniques and strategies are found in the literature:

3.1 Queuing theory

Yousef et al [19] developed their adaptive technique based on queuing theory, each movement at the intersection is modeled as M/M/1 queue with its own Arrival rate λ and departure rate μ , average queue length Q and average waiting time W. Using little's law $W = Q/\lambda$ and the queue length Q_j of the j^{th} cycle is given by the following formula:

$$Q_j = Q_{j-1} + \lambda T_G - \mu T_G + \lambda T_R \quad (1)$$

Q_{j-1} is the remaining vehicles from the previous cycle, T_G is the green light time and T_R is the red light time. The phases are formed using a conflict matrix and sorted to give priority to the movements with the highest queue lengths, the phase order determination is cycle based i.e. updated at the end of each cycle and the green time of each phase is set in accordance to discharge the movement that has the longest queue. For traffic detection, sensor nodes are placed in protected holes on the roads with two sensors for each lane (before and after the traffic light) to count vehicle arrivals and departures. All sensors communicate with a Base Station using TDMA protocol, the base station aggregates the received information and pass them to a Control Box where the TSTMA (Traffic Signal Time Manipulation Algorithm) is executed to set the appropriate order and timing of the different phases, the algorithm developed by the authors has an objective of reducing the AQL and the AWT. The simulation results show the advantage of using the adaptive traffic algorithm to dynamically control the traffic light in comparison with a fixed time control. The authors in their work assumed that all vehicles have the same speed and all sensor nodes were placed in the coverage range of the BS limiting their deployment and hence the efficiency of the system, also the distance between sensor nodes on each lane was not mentioned.

3.2 Score Function

The authors in [20] considered a single intersection of four directions (N, E, S,W) and two lanes for each direction. Two sensor nodes are placed on each lane, one at the junction and the other one at a distance $D = T_G^{Max}.V$ where T_G^{Max} is the maximum allowed green time and V is the speed of vehicles. The authors adopted 12 phases and

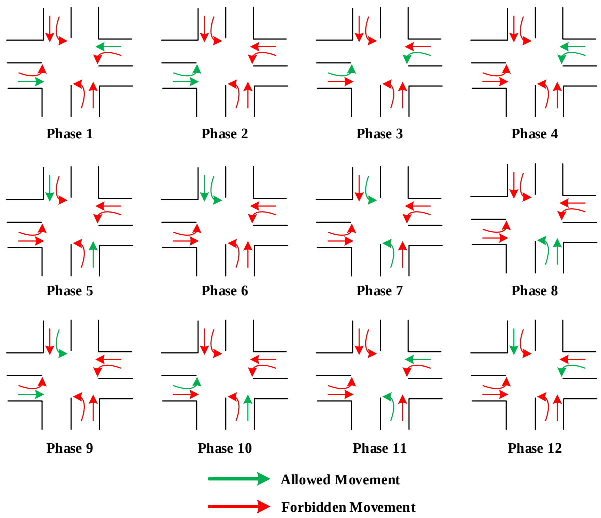

Fig. 2. All possible 12 phases

each phase has its own traffic light as shown in Figure 2. The proposed algorithm starts by detecting the departure and arrival rates, and the type of vehicles using the different sensor nodes. the next step of the algorithm uses the traffic information obtained from the previous step to set the sequence of the phases relying on a score function that reflects the degree of demand of a green light for each phase based on five weighted factors as follow:

$$SF = a_1 TV + a_2 W + a_3 HL + a_4 BC + a_5 SC \tag{2}$$

Where TV the traffic volume reflects the number of vehicles, W is the average waiting time, HL is the Hunger Level that reflects how many or how few a given phase has been attributed a green light before, the Hunger Level is used here to prevent famine i.e. a situation where a given phase is not selected for a long period of time. The Blank count (BC) reflects segments of a lane where no vehicle is present and how far these segments are from the intersection, the higher the BC the lower is the priority. Special Circumstances (SC)factor reflects special events like the presence of an emergency vehicle or accident where higher priority is given for an emergency vehicle and lower priority for an accident. The coefficients $a_1 \ldots a_5$ are set to give priorities for the previously mentioned factors from highest to lowest in a descending order as follow: SC, BC, HL, TV and finally waiting time W. The phase which has the highest value of SF is selected next to have a green light and the green time duration is set in a way that all the vehicles of the selected phase pass the intersection and is bounded by T_G^{Max}. Through simulation the authors demonstrated the superiority of their algorithm in comparison with an actuated and fixed time control systems in terms of reducing the average waiting time AWT and increasing throughput i.e. the rate of vehicle departures at the intersection. In the proposed algorithm, unrealistic assumptions are made as all vehicles are assumed to run at the same speed and also the turning right movements are not considered. In [21] the authors extended their work to cover multiple intersections, the green time of a phase is recalculated adding an offset to account for coming vehicles from neighboring intersections and hence creating green waves.

Like most of the literature Faye et al [22] use two sensor nodes per lane as shown in Figure 3 separated by a distance $D = N.L$ where L is the average vehicle length and N is the maximum number of vehicles allowed to pass when $T_G = T_G^{Max}$, $N = (T_G^{Max} - T_s)/T_h$ where T_s is the starting time when the light switches from red to green and T_h is the average time separating two discharging vehicles. All sensor nodes are assumed of the same type and have a magnetometer as a sensing element.

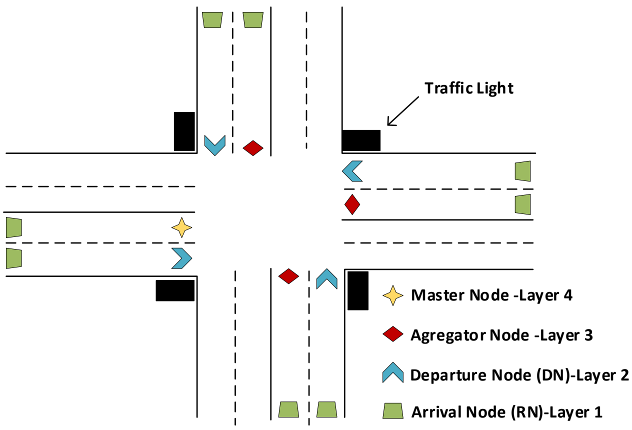

Fig. 3. Intersection Architecture

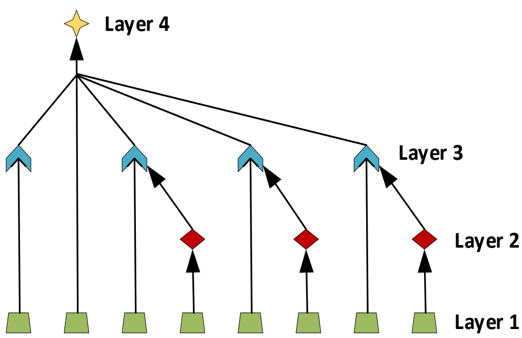

Fig. 4. Hierarchical Architecture

The architecture adopted by the authors follows a hierarchical scheme, Figure 4, where the sensors are distributed among four layers. Layer 1 is composed of Arrival Nodes (RN) counting the number of vehicles approaching the intersection on each lane and pass them to layer 2 nodes, Departure Nodes (DN) in layer 2 count the number of vehicles leaving the intersection and with the information received form layer 1, they keep track of the number of vehicles occupying each lane. Layer 3 nodes are elected among departure nodes to count the number of vehicles for each possible movement and also count the time since the movement was last selected. Similar to the idea in [21], the master node in layer 4 uses the information of layer 3 and assigns a score for each movement k based on the queue length and hunger level as follow :

$$SF_k = \alpha \cdot \left(\frac{N^k}{\sum_{p=1}^{M} N^p}\right) + \beta \cdot \left(\frac{T^k}{\sum_{p=1}^{M} T^p}\right) \quad (3)$$

Where $N^k$is the number of vehicles composing movement K, N^p number of vehicles composing a movement p where p =$[1..M]$, M is the number of all possible movements, T^k is the time elapsed since the movement K was last selected, α and β are weighting parameters allowing to favor one objective over the other. After setting a score for each movement, the master node combines all the simultaneous nonconflicting and slightly conflicting movements into phases and add up the corresponding scores to obtain a global score for each phase, the phase with the highest score is attributed a green light. Similar to [21] the green time of the selected phase is set to allow all the vehicles to pass the intersection and is equal to $T_G = T_s + T_h \cdot N_{max}$ where N_{max} is the largest number of vehicles found among the lanes composing the selected phase. As long as $T_G < T_G^{Max}$ T_G is extended by T_h for each vehicle detected by RN. Using SUMO (Simulation of Urban Mobility) software, the authors evaluated their adaptive algorithm on an intersection in the city of Amiens (France) and with the appropriate selection of T_G^{Max} and weighting parameters they obtained better AWT when compared to both the existing fixed time control of the Amiens' intersection and the algorithm proposed by Yousef et al in [20]. The advantage of the architecture used in this work is that layer 3 and layer 4 roles can be performed by any Arrival Node (RN) allowing high fault tolerance and unlike the works in [19], [20], the TLC here is merely an actuator applying the light plan set by layer 4 sensor, however the authors didn't include the emergency vehicles and eventual accidents in their algorithms like in [20] and also the choice of parameters was based on experimentation only.

In [23] Faye et al extended their work for multiple intersections in which they introduced two more new objectives in their score function to create green waves: 1) prevent overloading an intersection which already has enough vehicles and 2) take into account the number of vehicles coming from adjacent intersections, for these purpose the Departure Sensors (DS) were moved to the outgoing lanes instead of the incoming lanes in their previous work.

3.3 Fuzzy logic

In [24] the authors use a WSN based on IEEE 802.15.4 communication protocol and four parallel fuzzy logic controllers to dynamically set the timing of the green light for four possible phases i.e. one controller for each phase. Similar to Faye et al in [22], the authors use a hierarchical architecture where the sensor nodes are placed on the road-side of each lane and use magnetometers to collect traffic data.

The sensor nodes of each lane send the information to an aggregator node which assesses the queue length of the lane and transmit the information to the master node. Once the master node receives the number of vehicles on each lane from all the aggregator nodes, it sorts the different phases giving priority to the longest queue and apply the appropriate green light timing using the fuzzy logic controllers. The fuzzy controller is built following three steps: In the fuzzification process, the triangular input membership function characterizes the queue length of each lane as {Normal, Medium, Long} which corresponds to a number of vehicles per lane in the range of [16...80], the triangular output member function reflects the green light timing as {Min, medium, Max} corresponding to a range of [15s...90s]. In the second step, inference mechanism, an IF-Then rule is used to map the member functions. In the last step, defuzzification, the authors chose the Centroid Of Area (COA) method to obtain the crisp output representing the green light timing of the phase. Simulation was carried using MATLAB for the fuzzy logic controller and the TRUTIME toolbox to simulate IEEE 802.15.4 protocol. the authors compared their method with the fixed time control scheme and with three other fuzzy logic based methods from the literature. The multicontroller approach outperformed the previously mentioned methods in term of reducing the AWT especially in a high traffic situation. The authors suggested 240 sensor nodes per intersection, one for each vehicle detection, which is a huge number influencing the cost of the system. The intersection is assumed fixed meaning that the algorithm does not rely on a conflict matrix to dynamically compose the phases irrelative to the intersection configuration, also the control scheme adopted is cycle based and not phase based which makes the solution not fully adaptive.

3.4 Prioritizing Emergency vehicles

Krishna et al [25] developed a system to provide a free passage for emergency vehicles at intersections. sonar sensors and a camera were used to detect the emergency vehicles and switch the traffic lights in favor of a green wave. A prototype of the system was built using two traffic junction nodes and a communication node. The junction node is built around Raspberry-Pi processor and uses a USB camera to confirm and identify a passing emergency vehicle after being detected by a sonar sensor. Upon confirmation of a passing emergency vehicle, the junction node sends a signal to the traffic controller to properly adjust the lighting and another signal to all junction nodes of adjacent intersections through communication nodes. The communication node is built around Arduino UNO and an RF module, it is used as a message repeater between two junction nodes. The communication between the intersection node and the junction node is based on the ZigBee protocol. Simulation on a four-intersection path shows that the proposed system reduces the journey time of the emergency vehicle by 3 minutes compared to conventional fixed time control. the algorithm proposed by the authors affects all adjacent intersections irrelative to where the emergency vehicle goes next and thus induce more traffic jam, also if two or more emergency vehicles are present on the different roads of an intersection, priority is given based on the arrival time to the intersection rather than the degree of emergency.

4 Discussion and Enhancement Factors

All the previously discussed works share the same objective of reducing the average waiting time AWT, so comparing them with each other based on AWT minimization would imply having access to their detailed algorithms and apply them to the same set of intersections which is out of the scope of this paper. Instead we will compare them based on cost, adaptivity to traffic variation, flexibility to cope with different intersection configuration (single or multiple intersections) and some other factors presented in Table 3.1 as pros and cons for each technique.

In the reviewed works, authors focused on how to reduce average waiting time AWT of vehicles and some prioritized emergency vehicles in their algorithms but they didn't take into consideration some other important factors like pedestrians crossing the roads as an AWT for pedestrians could be considered by introducing for example some weight sensors near traffic lights pols to estimate the number of pedestrians waiting for a red light to cross the road. Reducing congestion emissions is also an important factor that could be added in designing an adaptive system especially in cities where air pollution is a huge issue, remote sensing units could be placed on road sides to measure emissions from vehicles. Making use of studies like the work in [8], discussed in section 2, for vehicle classification could be of great importance because treating a bus and a car alike is not practical especially if we seek reducing the average waiting time, as we all know a bus in peak hours is generally full of passengers going to work or school or returning from them, so adding priority to lanes with a bus or more could considerably reduce AWT per person rather than AWT per vehicle. Finally, when using a score function like the work in [20], [22], section 3, the weighting parameters could be optimized using mathematical techniques instead of experimentation, this would lead to a better average waiting time AWT.

Table 1. Comparative Table.

Approach	References	Pros	Cons
Queuing Theory	Yousef et al [19]	-Low Cost - Flexible (multiple intersections) -Applicable to different intersection configuration (Conflict Matrix)	-Not Fully Adaptive (Cycle Based) -Low Fault Tolerance -No emergency vehicle consideration -Famine situation is not considered
Scoring Function	Zhou et al [20] [21]	- Flexible -Highly adaptive (phase based) -Special events consideration -Famine situation consideration	-Predetermined intersection Configuration and phases -Weighted Factors selected experimentally
	Faye et al [22] [23]	- Flexible --Highly adaptive (phase based) -High Fault Tolerance -Low Cost	- No Special events consideration (accidents or emergency vehicles) -Weighted Factors selected experimentally

Fuzzy Logic	Collotta et al [24]	- High Fault Tolerance and high performance (One controller for each phase and multiple sensors)	- High Cost -No Special events consideration -Single intersection only -Predetermined phases
Prioritizing Emergency Vehicles	Krishna et al [25]	-Reduced Journey Time for Emergency Vehicles -Simple and Low Cost	-Increases Traffic Jams -For Multiple Emergency Vehicles, Priority is given based on arrival time

5 Conclusion

Managing intersections effectively using adaptive traffic light control systems as opposed to fixed time or preprogrammed control helps tremendously in alleviating congestion impacts in cities. In this paper we reviewed relevant works of designing an adaptive traffic control systems using WSN as a solution to the existing expensive techniques, we focused on the different sensing technologies employed to gather traffic information like AMRs and also on the algorithms and architectures used to increase throughput and reduce the average waiting time AWT including queuing theory, weighted score functions, fuzzy logic controllers. Furthermore, additional aspects for enhancing the performance of the reviewed works were discussed. As future work, we will try to design our own sensing node for traffic detection and also implement on it our own algorithm relying on the experience learned from the present state of the art.

References

1. J.P Rodrigue, The Geography of Transport Systems, Fifth Edition. New York, NY, USA: Routledge (2020).
2. D. Schrank, B. Eisele, and T. Lomax, “2019 Urban Mobility Report,” Texas A&M Transportation Institute, Texas, TX, USA (2019).
3. INRIX, “EMBOUTEILLAGES : UNE FACTURE CUMULEE DE PLUS DE 350 MILLIARDS D’EUROS POUR LA FRANCE SUR LES 16 PROCHAINES ANNEES,” Inrix. https://inrix.com/press-releases/embouteillages-une-facture-cumulee-de-plus-de-350-milliards-deuros-pour-la-france-sur-les-16-prochaines-annees/ last accessed 2020/05/19.
4. K. REMOUCHE, “Embouteillages : ce que ça coûte: Toute l’actualité sur liberte-algerie.com,” Embouteillages : Ce Que Ça Coûte. http://www.liberte.dz/actualite/embouteillages-ce-que-ca-coute-291453 last accessed 2020/05/19.
5. HSPH, “Emissions from traffic congestion may shorten lives,” News. https://www.hsph.harvard.edu/news/hsph-in-the-news/air-pollution-traffic-levy-von-stackelberg/ last accessed 2020/06/13.
6. S. Faye, “Contrôle et gestion du trafic routier urbain par un réseau de capteurs sans fil,” Ph.D. dissertation, Paris Institute of Technology, Paris, France (2014).
7. G. Padmavathi, D. Shanmugapriya, and M. Kalaivani, “A Study on Vehicle Detection and Tracking Using Wireless Sensor Networks,” Wirel. Sens. Netw., vol. 02, no. 02, pp. 173–185 (2010).

8. X. Chen, X. Kong, M. Xu, K. Sandrasegaran, and J. Zheng, "Road Vehicle Detection and Classification Using Magnetic Field Measurement," IEEE Access, vol. 7, pp. 52622–52633 (2019).
9. M. Liu, W. Hua, and Q. Wei, "Vehicle detection using three-axis AMR sensors deployed along travel lane markings," IET Intell. Transp. Syst., vol. 11, no. 9, pp. 581–587 (2017).
10. B. Santoso, B. Yang, C. L. Ong, and Z. Yuan, "Traffic Flow and Vehicle Speed Measurements using Anisotropic Magnetoresistive (AMR) Sensors," in 2018 IEEE International Magnetics Conference (INTERMAG), pp. 1–4, Singapore (2018).
11. J. Gajda and M. Stencel, "A Highly Selective Vehicle Classification Utilizing Dual-Loop Inductive Detector," Metrol. Meas. Syst., vol. 21, no. 3, pp. 473–484 (2014).
12. S. V. Bhate, P. V. Kulkarni, S. D. Lagad, M. D. Shinde, and S. Patil, "IoT based Intelligent Traffic Signal System for Emergency vehicles," in 2018 Second International Conference on Inventive Communication and Computational Technologies (ICICCT), pp. 788–793, Coimbatore (2018).
13. S. R. E. Datondji, Y. Dupuis, P. Subirats, and P. Vasseur, "A Survey of Vision-Based Traffic Monitoring of Road Intersections," IEEE Trans. Intell. Transp. Syst., vol. 17, no. 10, pp. 2681–2698 (2016).
14. Siemens, "Deploying SCOOT in Seattle," Austin, TX, USA, Project White Paper, 2017.
15. [16] Siemens, "Keeping Traffic Moving in Ann Arbor", Project White Paper, Austin, TX, USA (2016).
16. Y. Zhao and Z. Tian, "An Overview of the Usage of Adaptive Signal Control System in the United States of America," Appl. Mech. Mater., vol. 178–181, pp. 2591–2598 (2012).
17. NSW, "SCATS and Intelligent Transport Systems," SCATS, Feb. 27, 2020. http://scats.nsw.gov.au/ last accessed 2020/06/21.
18. M. Selinger, PTOE, and L. Schmidt, "Adaptive Traffic Control Systems in the United States," HDR Engineering (2009).
19. K. M. Yousef, J. N. Al-Karaki, and A. M. Shatnawi, "Intelligent Traffic Light Flow Control System Using Wireless Sensors Networks," J. Inf. Sci. Eng., vol. 26, pp. 753–768 (2010).
20. B. Zhou, J. Cao, X. Zeng, and H. Wu, "Adaptive Traffic Light Control in Wireless Sensor Network-Based Intelligent Transportation System," in 2010 IEEE 72nd Vehicular Technology Conference - Fall, Ottawa, ON, pp. 1–5, Canada (2010).
21. B. Zhou, J. Cao, and H. Wu, "Adaptive Traffic Light Control of Multiple Intersections in WSN-Based ITS," in 2011 IEEE 73rd Vehicular Technology Conference (VTC Spring), pp. 1–5, Budapest, Hungary (2011).
22. S. Faye, C. Chaudet, and I. Demeure, "A distributed algorithm for adaptive traffic lights control," in 2012 15th International IEEE Conference on Intelligent Transportation Systems, Anchorage, pp. 1572–1577, AK, USA (2012).
23. S. Faye, C. Chaudet, and I. Demeure, "A distributed algorithm for multiple intersections adaptive traffic lights control using a wireless sensor networks," in Proceedings of the first workshop on Urban networking - UrbaNe '12, p. 13, Nice, France (2012).
24. M. Collotta, L. Lo Bello, and G. Pau, "A novel approach for dynamic traffic lights management based on Wireless Sensor Networks and multiple fuzzy logic controllers," Expert Syst. Appl., vol. 42, no. 13, pp. 5403–5415 (2015).
25. A. A. Krishna, B. A. Kartha, and V. S. Nair, "Dynamic traffic light system for unhindered passing of high priority vehicles: Wireless implementation of dynamic traffic light systems using modular hardware," in 2017 IEEE Global Humanitarian Technology Conference (GHTC), pp. 1–5, San Jose, CA (2017).